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Do mariculture products offer better environment and nutritional choices compared to land-based protein products?

Abstract: Mariculture products are generally deemed to have less negative environmental externalities and more nutrient content, and are therefore a promising food substitute for land-based protein products (LPPs). China is the world's largest mariculture producer, with 66% of global production share in 2018. However, different categories of mariculture products have varied nutrient composition and environmental impacts, and ignoring such heterogeneity potentially misleads policy decision making in mariculture development in China. Here, we compare the environmental and nutritional performance of 28 mariculture products with 7 LPPs produced in China. Our results show that although mariculture products are more environmentally friendly than LPPs on the whole, not all mariculture products have better nutrition-environmental performance than LPPs. Only 17 out of 28 mariculture products, mainly shellfish and fish, are found to be both nutritionally and environmentally more friendly than LPPs. Shellfish are promising substitutes for LPPs due to their minor environmental impact, higher nutrient density, greater production volume and lower average price compared with other mariculture products. However, upper dietary limits on daily intake of shellfish due to potential overconsumption of certain micronutrients must also be considered. We also found mariculture derived fish have no distinct environmental, nutritional or cost benefits over some LPPs, such as egg and chicken. The current structure of the mariculture industry in China may be optimized by expanding the production of nutrient-rich mariculture products with low environmental impact and affordable price.

Keywords: mariculture products, land-based protein products (LPPs), water footprint, nitrogen footprint, nutrient density.

1. Introduction

Under the UN's medium growth scenario global population is expected to reach 9.7 billion by 2050 (UN, 2019). The concurrent demand for food and nutrition will lead to huge pressure on natural resources and the environment on a global scale (Tilman et al., 2017; FAO, 2020; Singh et al., 2021; Froehlich et al., 2018). Current protein supply is dominated by land-based protein products (LPPs), which is one of the main causes of environmental damage and climate change (Hilborn et al., 2018). The production of LPPs emits 19-29% of global greenhouse gas emissions (Vermeulen et al., 2012), consumes more than 70% of the world's water resources (Hoekstra and Mekonnen, 2012), and is the main contributor to nitrogen pollution (Mueller and Lassaletta, 2020). Despite this we fail to meet global nutritional needs (Golden et al., 2021); globally 820 million people are undernourished (Willett et al., 2020), and 30% of the population fall short of at least one micronutrient in their diet (DIPR, 2020).

Seafood is rich in micronutrients and is generally regarded as conferring lower levels of environmental stress than LPPs (Golden et al., 2021; Stentiford et al., 2020; Liu et al., 2018). According to recent studies, choosing seafood as an alternative protein source shows promise in meeting nutritional and environmental goals (Vanham et al., 2013; Bogard et al., 2018; Tilman and Clark, 2014). Seafood production may be categorised into two groups, namely capture fishery and mariculture. Capture fishery plays an important role in the global supply of aquatic products, but its expansion has been limited by capacity of the aquatic ecosystem and associated regeneration rates (Foley et al., 2012). The fast expansion of capture fishery has resulted in significant depletion of fish stocks (Golden et al., 2016). In contrast, mariculture has potential for growth due to its comparatively minor impact on marine ecosystems and recent technological advances (Merino et al., 2012). Although only 5% of global protein production is currently derived from mariculture (FAO, 2020; FAO, 2021), the amount of food produced from mariculture is likely to meet 5-19% of the estimated increase in total protein demand of 9.7 billion people in 2050 (Costello et al., 2012).

Despite this, concerns have also been raised regarding the environmental and nutritional benefits of mariculture products. Firstly, some mariculture products rely on feed sources from land-based agriculture (Newton and Little, 2018; Little et al., 2018), and the resulting environmental impacts of this cannot be ignored (Froehlich et al., 2018). Secondly, most previous studies treated seafood as a broad category of products to be analyzed together with other food groups (Koehn et al., 2022; Shalders et al., 2022; Wang et al., 2022). Plenty of previous researches have also tended to focus on limited species of mariculture products, mostly fish (Pelletier et al., 2009; Yuan et al., 2017), whilst other species such as shellfish or crustacean are seldom considered (Driscoll et al., 2015; Nanda et al., 2021; Mititelu et al., 2022). To address these concerns, our research approach has been to build a complete list of nutrition and environmental inventories for different mariculture products in order to examine the differences in nutrient content, environmental impact, cost and production.

Carbon emissions have usually been the only selected environmental indicator (Madin and Macreadie, 2015), with studies concluding that proteins harvested from the sea have a significantly lower carbon footprint than proteins derived from land animals particularly ruminants (Hilborn et al., 2018; Madin and Macreadie, 2015; Tilman and Clark, 2014; Poore and Nemecek, 2018; Godfray et al., 2010). With regard to land use, a recent study concluded that mariculture will continue to rely more on land-based, rather than sea-based, feed sources inputs (Zhang et al., 2022). Given that the key biophysical drivers of crop yield are addition of water and fertiliser, water and nitrogen footprints seem most relevant to crop-based feed production, but are rarely evaluated in mariculture (Mueller et al., 2012).

China is the world’s leading producer of mariculture products, accounting for around 66% of total global production in 2018 (FAO, 2020; FBCM, 2019). Over the past 20 years, China has produced more than 60 million tons of seafood annually. Mariculture accounted for more than 70% of China's seafood output in 2018. Between 1986 and 2018, China’s mariculture production increased around 13 times (FBCM, 2019; FAO, 2021). In the present study, we undertook analysis based on China’s mariculture. We first evaluated the environmental and nutrient performance of 28 different mariculture products using 2018 as the year base. The mariculture products included 10 species of fish, 6 species of crustacean, 9 species of shellfish and 3 other classes. The environmental indicators we used included water footprint and nitrogen footprint, and nutrient density was used as the nutritional indicator. We further compared the results from our mariculture product findings with seven selected LPPs. Overall, this analysis is distinguished from previous studies through (1) providing a full list of nutrition and environmental inventories for specific mariculture products; and (2) considering environmental impact indicators most relevant to crop-based feed production i.e., water footprint and nitrogen footprint. We believe our findings help identify opportunities for achieving sustainable diets through mariculture production, contributing to the UN SDG's of Zero Hunger (Goal 2), Responsible Consumption and Production (Goal 12), and Life Below Water (Goal 14).

2. Methods and data

2.1 Water footprint accounting

The water footprint of a product is the volume of freshwater used to produce the product (Mekonnen and Hoekstra, 2011). The water footprint consists of green water, blue water and grey water. The green water footprint refers to the consumption of rainwater. The blue water footprint refers to the consumption of surface water and groundwater. The grey water footprint refers to the volume of freshwater required to assimilate pollutant loads based on natural background concentrations and existing environmental water quality standards (Hoekstra et al., 2011). Since the grey water footprint aligns with environmental pollution and has some overlap with the contents measured by the nitrogen footprint (Mekonnen and Hoekstra, 2012), the grey water footprint is only shown in the Appendix (Table S6).

In this paper, the water footprint of LPPs was derived from the Global Water Footprint Database (Mekonnen and Hoekstra, 2011; Mekonnen and Hoekstra, 2012). The database contains average water footprint of 352 plant products and 106 animal products in China. For mariculture products, the water footprint consists of direct (related to mariculture process) and indirect (related to feed input) water footprint of mariculture. The direct water footprint of mariculture was assumed to be 0, because the water footprint of this study only involved freshwater rather than seawater. We adopted the method recommended by Pahlow et al. (2015) to calculate the indirect water footprint of mariculture, i.e., the water footprint of the feed input for the production of mariculture products.

$$WF_{m,i} = \frac{\sum_{f=1}^{n_1}\left(WF_{i,f}\times\sum_{r=1}^{n_2}\frac{I_{i,f,r}}{n_2}\right)\times FCR_i \times P_i}{E_i} \quad (1)$$

$$WF_{p,i} = WF_{m,i} \times \frac{100}{w_p} \quad (2)$$

$$WF_{e,i} = WF_{m,i} \times \frac{100}{w_e} \quad (3)$$

$$WF_i = WF_{m,i} \times Y_i \times E_i \quad (4)$$

Where $WF_{m,i}$ (L g^{-1}) is the water footprint per gram (UWF, the unit is L g^{-1}) of mariculture product *i*; $WF_{i,f}$ (L g^{-1}) is the UWF of raw material *f* in the standard feed formula of mariculture product *i*; and n_1 is the number of raw material *f* in the standard feed formula of mariculture product *i*; $I_{i,f,r}$ (g g^{-1}) is the weight of raw material *f* in the feed formula *r* of mariculture product *i*; n_2 is the number of feed formula of mariculture product *i*; FCR_i is the feed conversion rate of mariculture product *i*; P_i is the feeding ratio of mariculture product *i*; E_i is the edible part of the product, that is, the proportion of uncooked products following removal of all inedible parts. $WF_{p,i}$ (L g^{-1}) is the water footprint per gram of protein of mariculture product *i*; w_p (g) is the protein content per 100g mariculture product *i*. $WF_{e,i}$ (L kcal^{-1}) is the water footprint per calorie of mariculture product *i*; w_p (kcal) is the calorie per 100g mariculture product *i*. WF_i (m^3) is the total water footprint (TWF, the unit is m^3) of mariculture product *i*; Y_i (kg) is the production of mariculture product *i* in China in 2018.

Feed formulas affect the UWF. Based on the standard feed formula database of the China Fisheries Data Center (CFDC, 2019), FishBase (WFD, 2019) and patent database (PD, 2019), 167 officially recommended feed formulas were selected to calculate the standard feed formulas for 28 mariculture products (Table S2). We overlooked trace components in the feed formulation due to lack of data. The UWF of fish meal and fish oil were assumed to be zero (Gephart et al., 2014).

The UWF of feed ingredients was obtained from the Global Water Footprint Database (Table S3) (Aldaya et al., 2012). Our study selected feed ingredients with available green, blue and grey UWF data of Chinese provinces in 2018, simulated10,000 times in Monte Carlo in order to achieve the probability distribution and related statistical parameters.

2.2 Nitrogen footprint accounting

The nitrogen footprint is defined as the total amount of nitrogen released into the environment by an entity's consumption and associated food and energy production (Leach et al., 2012). The nitrogen footprint of food production represents all nitrogen losses along the food production chain to food consumption (Galloway and Leach, 2016). Here, for plant products, we only considered four steps of nitrogen flows: 1) the input of new nitrogen, 2) crop production, 3) crop harvest, and 4) plant food processing. For animal-based products, we considered six steps of nitrogen flow: 1) the input of new nitrogen, 2) feed production, 3) feed processing, 4) animal production, 5) animal slaughter, and 6) processing of animal-derived foods. In order to be consistent with water footprint accounting we didn’t consider further nitrogen losses in other steps, including food consumption.

The nitrogen footprint of LPPs was derived from the data set published by Hu et al. (2020), which contains nitrogen emissions from common agricultural and animal product production processes (Table S10). The nitrogen footprint of mariculture products was not included in this data set. Therefore, we calculated the nitrogen footprint per gram (UNF, the unit is g g^{-1}) of feed in mariculture products, and then calculated the production UNF of mariculture products based on the coefficient ratio of the production UNF to the UNF from feed:

$$NF_{m,i} = \frac{\sum_{f=1}^{n_1}\left(\frac{NF_{i,g}}{NCF_{f,g}} \times \sum_{r=1}^{n_2}\frac{I_{i,f,r}}{n_2}\right) \times FCR_i \times P_i \times NC_i}{E_i} \qquad (5)$$

$$NF_{p,i} = NF_{m,i} \times \frac{100}{w_p} \qquad (6)$$

$$NF_{e,i} = NF_{m,i} \times \frac{100}{w_e} \qquad (7)$$

$$NF_i = NF_{m,i} \times Y_i \times E_i \qquad (8)$$

Where $NF_{m,i}$ (g g^{-1}) is the UNF of mariculture product *i*; $NF_{i,g}$ (g g^{-1}) is the UNF of primary product g of raw material *f* in the standard feed formula of mariculture product *i*; $NCF_{f,g}$ is the nitrogen conversion coefficient of raw material *f* and its primary product g (FAO, 2015); n_1 is the number of raw material *f* in the standard feed formula of mariculture product *i*; $I_{i,f,r}$ (g g^{-1}) is the weight of raw material *f* in the feed formula *r* of mariculture product *i*; n_2 is the number of feed formula of mariculture product *i*. FCR_i is the feed conversion rate of mariculture product *i*;

P_i is the feeding ratio of mariculture product *i*; NC_i is the coefficient ratio of the production UNF of mariculture product *i* to the UNF from feed (Oita et al., 2016); E_i is the edible part of the product. $NF_{p,i}$ (g g^{-1}) is the nitrogen footprint per gram of protein of mariculture product i; w_p (g) is the protein content per 100g mariculture product i. $NF_{e,i}$ (g $kcal^{-1}$) is the nitrogen footprint per calorie of mariculture product i; w_p (kcal) is the calorie content per 100g mariculture product i. NF_i (t) is the total nitrogen footprint (TNF, the unit is t) of mariculture product *i*, and Y_i (kg) is the output of Chinese mariculture product *i* in China in 2018.

2.3 Nutrient density

The nutrient density of mariculture products was quantified according to a nutrient density scoring method recommended by Hallstrom et al. (2019). The formula used to calculate the nutrient density score is as follows:

$$NDS\text{-}A = \sum_{i=1}^{x} \frac{Nutrient_i}{DRI_i} - \sum_{j=1}^{y} \frac{Nutrient_j}{MRI_j} \tag{9}$$

Where *x* is the quantity of ideal nutrients *i*; *y* is the quantity of non-ideal nutrients *i*; $Nutrient_i$ is the content of ideal nutrients *i* in per 100 g raw mariculture products; $Nutrient_j$ is the content of non-ideal nutrients *j* in per 100 g raw mariculture products; DRI_i is the daily recommended intake of ideal nutrients *i*; and MRI_j is the maximum recommended daily intake of non-ideal nutrients *j*. Equation (9) takes the mass of mariculture products as the reference value and, by comparison, the nutritional density score is also calculated with the protein and calorie of mariculture products as the reference value:

$$NDS\text{-}B = \sum_{i=1}^{x} \frac{Nutrient_i}{DRI_i} \times \frac{100}{P_i} - \sum_{j=1}^{y} \frac{Nutrient_j}{MRI_j} \times \frac{100}{P_i} \tag{10}$$

$$NDS\text{-}C = \sum_{i=1}^{x} \frac{Nutrient_i}{DRI_i} \times \frac{100}{E_i} - \sum_{j=1}^{y} \frac{Nutrient_j}{MRI_j} \times \frac{100}{E_i} \tag{11}$$

Here, $Nutrient_i$ and $Nutrient_j$ in *NDS-B* is the content of deal nutrients *i* and non-ideal nutrients *j* in per 100 g protein of raw mariculture products, and P_i is the protein content per 100 g of raw mariculture products. In *NDS-C*, $Nutrient_i$ and $Nutrient_j$ is the content of deal nutrients *i* and non-ideal nutrients *j* in per 100 kcal of raw mariculture products, and E_i is the calorie per 100 g of raw mariculture products.

Nutrient content data was mainly obtained from the China Food Composition Database (NINH, 2018; NINH, 2019). Nutrient content refers to the nutrient content of an uncooked product, excluding inedible parts (such as bones, skin and shells). The nutritional content of the mariculture product refers only to the edible portion. For LPPs, the nutritional value used was a weighted average based on the nutritional content of the different parts of the animal and their respective weight ratios in the total weight of the boneless carcass of the animal. A total of 22 nutrients were included in the nutritional assessment, amongst which sodium and saturated fatty acids were classified as non-ideal, and all other nutrients were classified as ideal (Table S12). Reference values (Table S13) included the recommended daily intakes (*DRI*) of ideal nutrients and the maximum recommended daily intakes (*MRI*) of non-ideal nutrients (CSN, 2016; CSN, 2014). The reference value was expressed for the general population aged 18 to 65 years, and the average value was used for gender-specific recommended nutrients.

3. Results

3.1 Water footprint and nitrogen footprint of 28 mariculture products

Our results show the UWF of different mariculture products varied significantly (Fig. 1a). Amongst the 28 mariculture products, Chinese white shrimp and mud crab had the highest UWF (4.76 L g^{-1} and 4.56 L g^{-1}, respectively), whilst jellyfish and sea cucumber had the lowest UWF (0.05L g^{-1} and 0.01 L g^{-1}, respectively). Aggregating individual mariculture products into different categories we found crustacean had the highest UWF, followed by fish, shellfish, and other classes (Table S5). In comparison to LPPs, mariculture products had significantly lower UWFs. The production weighted average UWF for 28 mariculture products was 0.47L g^{-1} (SD: 0.002; [95%CI: 0.40, 0.55]) (green water accounted for 89.27%, blue water accounted for 10.73%), which was about one eighth of the UWF for LPPs (3.84 L g^{-1}). Such a large difference may be explained by their feed ingredients and feed conversion rate, i.e. total feed divided by total species group biomass increase, whereby the lower the conversion rate the higher the conversion efficiency (Table S4) (Boyd et al., 2007). The feed ingredients of LPPs were mainly animals and grains with high UWF, and the feed conversion rate of LPPs ranged between approximately 2.00 and 8.00 (Mekonnen and Hoekstra, 2012). In contrast, between around 30.00% and 60.00% of mariculture products' feed ingredients came from fish meal and miscellaneous fish with UWF close to zero. The average feed conversion rate of mariculture products was also lower (1.52) compared to that of LPPs (Tables S2-S4).

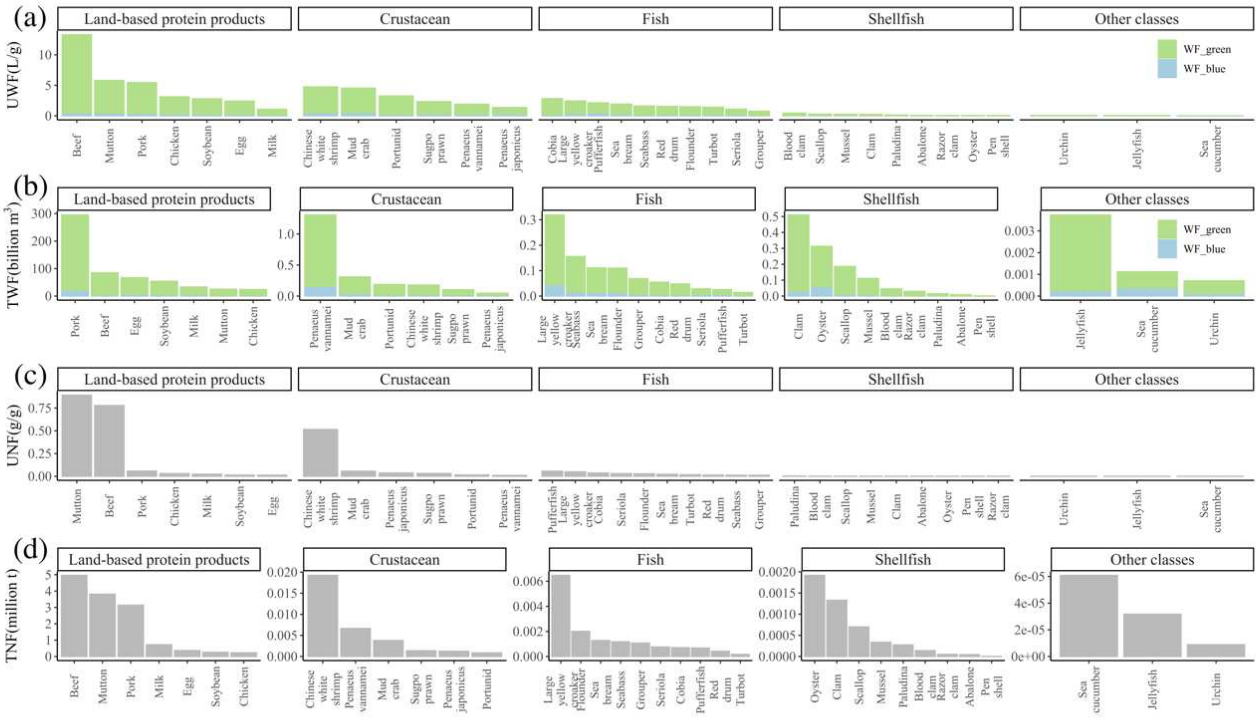

Fig. 1. Environmental indicators of mariculture products and LPPs in China in 2018. (a) UWF; (b) TWF; (c) UNF; (d) TNF. The bar charts categorize the water and nitrogen footprints of 28 mariculture products (10 fish, 6 crustacean, 9 shellfish and 3 other classes) and 7 LPPs (beef, mutton, pork, chicken, milk, egg and soybean). Calculation of water footprint and nitrogen footprint refers to the corresponding index of edible parts of the product.

However, not all mariculture products had lower UWF than LPPs (Fig. 1a). Some products, categorized within crustacean and fish, had higher UWF than certain LPPs. For example, the UWF of crustacean including Chinese white shrimp (4.76 L g^{-1}), mud crab (4.56 L g^{-1}) and portunid crab (3.28 L g^{-1}) were higher than that of chicken (3.12 L g^{-1}), soybean (2.80 L g^{-1}), egg (2.43 L g^{-1}) and milk (1.08 L g^{-1}). Cobia (2.82 L g^{-1}) and large yellow croaker (2.44 L g^{-1}) within the fish category had higher UWF than egg and milk. These mariculture products therefore had no obvious water saving advantage compared to the selected LPPs.

Similarly, the TWF of mariculture products was significantly lower than for LPPs in China (Fig. 1b). In 2018, the TWF of the 28 mariculture products produced in China was 4.29 billion m^3 (88.67% for green water and 11.33% for blue water), compared with 582.31 billion m^3 for LPPs. The TWF of different mariculture products varied significantly by category. Crustacean had the largest TWF, accounting for 49.63% of the TWF of mariculture products, followed by shellfish (28.44%), fish (21.80%) and other classes (0.13%) (Table S8). The large TWF of crustacean was mainly due to Chinese white shrimp, which contributed 61.32% of total TWF of crustacean.

We observed similar results for UNF, which for mariculture products (0.01g g^{-1}) was significantly less than that of LPPs (0.09 g g^{-1}) (Fig. 1c). Amongst all mariculture products and LPPs, mutton had the highest UNF of 0.89 g g^{-1} nitrogen pollution, followed by beef (0.78 g g^{-1}), whilst shellfish and other mariculture classes had the lowest UNF.

However, not all mariculture products had smaller UNF than LPPs. The production weighted average UNF of crustacean (0.03 g g^{-1}) and fish (0.03 g g^{-1}) were higher than that of chicken (0.03g g^{-1}), milk (0.02 g g^{-1}), soybean (0.01 g g^{-1}) and egg (0.01 g g^{-1}) (Tables S10-S11). The UNF of Chinese white shrimp (0.52 g g^{-1}) was ranked third highest in terms of nitrogen emissions, after mutton and beef. This is because the feed formulations for Chinese white shrimp contain large proportions (about 40%) wheat bran and meat powder, which are higher than for other mariculture products (Fig. 1c, Table S2).

The combined TNF of mariculture products was 0.05 million tons in 2018, largely derived from Chinese white shrimp (36%). In contrast, the TNF of LPPs was much larger ranging from 0.23 to 4.96 million tons (Table S11). We also quantified the water and nitrogen footprints per gram protein and per calorie. These results show that obtaining calories and protein from mariculture products, especially non-crustacean, generally needed less water and had lower nitrogen pollution than from LPPs (Figs. S1-S2, Tables S7-S8).

3.2 Nutrient density of mariculture products

We calculated the nutrient density score for mariculture products and LPPs using 18 micronutrients and 4 macronutrients. Three indicators were used, including mass (*NDS-A*), protein (*NDS-B*) and calorie (*NDS-C*) (see methods). The nutrient density score of mariculture products and LPPs in China using *NDS-A* is presented in the main text (Fig. 2), and *NDS-B* and *NDS-C* in the Appendix (Tables S14-S16). In general, mariculture products showed better nutritional quality properties with an average nutrient density score of 7.65, which was higher than that of LPPs (3.06). Most LPPs were ranked in the bottom half amongst all products in terms of their nutrient density (Table S16). However, there were some examples of LPPs with very high nutrient density scores. For example, the nutrient density score of soybean (10.60) was higher than most mariculture products, except oyster (12.13) and mud crab (11.37). The nutrient density score of mutton (4.24) was higher than many crustacean and fish. The nutrient density of some fish (grouper, large yellow croaker, turbot and pufferfish) was ranked in the bottom ten, with rankings close to those of chicken and pork. The lower nutritional performance of some fish may be attributed to the lower content of ideal nutrients (iron, zinc, etc), or that the content of undesired nutrients (sodium and saturated fatty acids) was higher, compared to other mariculture products (Table S12).

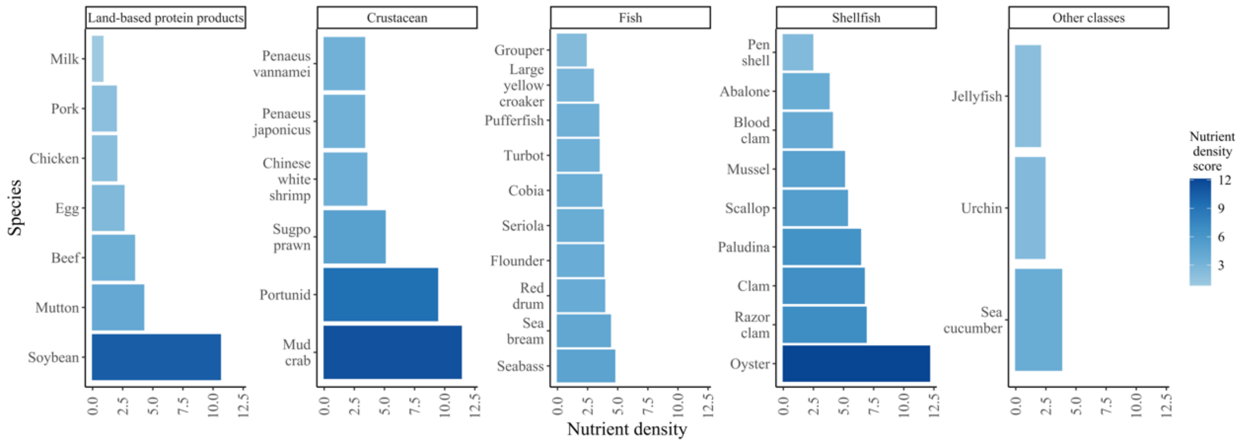

Fig. 2. Nutrient density scores of mariculture products and LPPs in China, based on classification and individual product. Color depth indicates the nutrient density score of various products; the darker the color, the higher the nutrient density. Calculation of nutrient density score relates to the corresponding index of the edible part of the product.

The high nutrient density scores of mariculture products were mainly due to their high micronutrient content (Fig.S6). However, the effects of various micronutrients on nutrient density score varied between mariculture products and LPPs (Table S18). Copper, selenium and vitamin

B12 were the main micronutrients contributing to the nutrient density score of mariculture products, by more than 10% respectively. The nutrients contributing most to the nutrient density score of land-based animal protein products were zinc, copper and vitamin B12. For land-based plant protein soybean, the effects of vitamin E, copper and omega-3 on nutrient density fractions were more than 10% respectively. Vitamin B12 was mainly contained in meat and seafood.

3.3 Win-win and trade-off relationships between mariculture products and LPPs

Combining nutrient density indicators and environmental indicators (UWF and UNF) for 28 mariculture products and 7 LPPs, we grouped all products into four quadrants (Fig. 3). We also compared the combined nutritional and environmental impacts of different products on a protein and calorific basis (Figs. S7-S8), which showed a similar pattern as in Fig. 3. Products in quadrant II were both nutritionally and environmentally friendly. We found 17 out of 28 mariculture products were distributed in quadrant II (Fig. 3), which was dominated by fish and shellfish. Soybean was the only LPP in quadrant II. However, the production volume of products in quadrant II only accounted for 19% of the total production volume of all products. LPPs were mainly distributed in quadrants III and IV where the nutrient density was lower than the mean value (3.49). Our results also showed LPPs had a lower price and greater production volume than mariculture products (Fig. 3). Generally, mariculture products were distributed in quadrants II and III, where the environmental impact was lower than the mean values (3.52 L g^{-1} for UWF and 0.08 g g^{-1} for UNF).

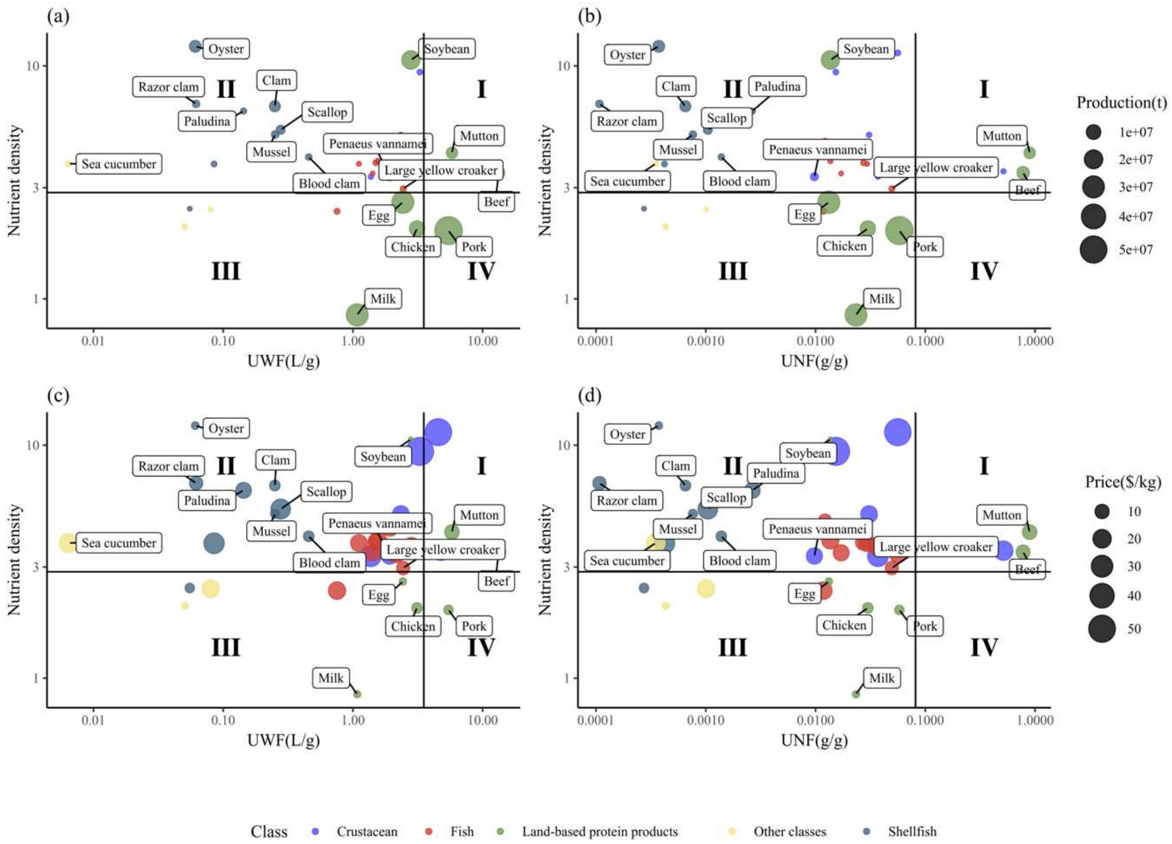

Fig. 3. Comparison of environmental and nutritional impacts of mariculture products and LPPs in China in 2018. Fig. a and Fig. c show the relationship between UWF and nutrient density; Fig. b and Fig. d show the relationship between UNF and nutrient density. The size of the bubbles in Fig. a and Fig. b represents the total production of each product in 2018 (FBCM, 2019; SBPR, 2019). The size of the bubbles in the Fig. c and Fig. d reflects the price of each product in 2018 (edible part only) (RSE, 2019). The color of the bubbles indicates the category of product, and the crosshair in the center is based on the weighted average of all products. Products with labels represent the top half of products by production volume. Each chart has four quadrants, namely; high nutrition and high environmental impact (quadrant I), high nutrition and low environmental impact (quadrant II), low nutrition and low environmental impact (quadrant III), and low nutrition and high environmental impact (quadrant IV).

Looking at the price of mariculture products and LPPs, we found the average price of mariculture products in quadrant II was relatively high. Products in quadrant III were more environmentally friendly but had less nutritional density. Overall, we found shellfish in quadrants

II and III had greater production volume, accounting for 84.5% of total mariculture production, but had a lower average price than other mariculture product categories. Fish in quadrant III had no obvious advantage in terms of environmental impact compared with egg, chicken and milk, which were also cheaper.

Only two species in crustacean (Chinese white shrimp and mud crab), and three LPPs (beef, pork and mutton) were located in quadrants I and IV, which had greater environmental impacts than for other products. Pork was located in quadrant IV for UWF, but in quadrant III for UNF. In contrast, mud crab was located in quadrant I for UWF, but in quadrant II for UNF. Pork had an overwhelming production volume compared to other products, but a relatively lower price.

4. Discussion

Our findings reveal that obtaining nutrients from mariculture products as a whole was more environmentally friendly than getting them from LPPs. However, different categories of mariculture products varied greatly in terms of environmental impact and nutritional value. Not all mariculture products are ideal substitutes for LPPs when considering environmental impact, nutritional performance and price. The current structure of the mariculture industry in China may be optimized by expanding the production of nutrient-rich mariculture products with low environmental impact and affordable price.

Amongst all categories of mariculture, shellfish showed most promise in acting as a substitute for LPPs. First, shellfish have greater production expansion potential than other mariculture products in China. Large-scale shellfish farming in China started in the 1950s, which currently accounts for greater than 85% of global production (Willer and Aldridge, 2020). The case in China also demonstrates the economic viability of shellfish farming in a rapidly developing country; with innovation in production technology, shellfish could meet the protein requirements of nearly 1 billion people in the most vulnerable regions of the world (Willer and Aldridge, 2020). Second, apart for a few shellfish (abalone and paludina) that rely on artificial bait and compound feed, most shellfish do not require feed inputs, so the overall environmental footprint of shellfish is small. Shellfish are rich in micronutrients, which help supplement micronutrient deficiencies in China. In addition, the price of shellfish is the lowest amongst mariculture products, and is becoming an affordable seafood option for consumers. Shellfish may therefore be an accessible nutrient route for populations in developing countries.

However, it should be cautioned that there are upper limits on daily intake of shellfish (Table S19). Micronutrients (copper, zinc, iron, selenium, etc.) are ideal nutrients that have a positive effect on health when consumed in moderation, but may have toxic effects when the recommended daily intake limits are exceeded. Taking oyster as an example, which has the highest nutrient density, frequent or large-scale consumption should be avoided due to its high copper content (8.13mg/100g) compared to the recommended daily intake (0.80mg/d) (Table S12). Hence, shellfish such as abalone, razor clam, cockle and oyster should only amount to less than 15% of daily protein intake when taking recommended nutritional limits into consideration. Upper daily intake limits may therefore constrain the development these shellfish production industries as a substitute for LPPs. Moreover, our results indicate a combination of mariculture and LPPs should be adopted to meet the nutritional requirements of the human body, whilst balancing environmental and economic requirements (He et al., 2018).

Fish are beneficial to human health due to their plentiful supply of micronutrients such as omega-3. However, several factors potentially constrain the further development of the mariculture fish industry. First of all, there is no significant advantage in price or nutrition for fish. Compared to shellfish, fish have a lower nutrient density but are more expensive. Compared with LPPs, the nutrient density of fish is similar to LPPs, but the price of fish is higher than LPPs. Secondly we found fish, largely because of their feed, had no obvious environmental advantage compared to some LPPs. Fish feed mainly consists of two elements, one is derived from land (soybean meal, wheat meal, meat and bone meal, etc.) and the other is fish meal and fish oil derived from wild fish. The former has a large environmental impact, whilst the latter, although the UWF and UNF are close to zero, is unsustainable in terms of the nature of capture fisheries. To solve this dilemma, the combined effects of fisheries reform, reducing the use of non-carnivorous mariculture in feed, and innovating new feed ingredients will help limit the environmental impact of mariculture feeds in the future.

To ensure the development of mariculture products with lower environmental impact, higher nutritional density and affordable price in China, efforts should first be made to expand the production base. Increased production will require significant investment and innovation in mariculture infrastructure including farming facilities, transportation, cooling and processing (Vanham et al., 2013). For example, the transportation and storage costs of frozen shelled products are significantly lower than those of fresh shelled products. Innovative financial methods, such as microfinance, will also boost the mariculture industry. In Peru, for example, a 50% corporate tax cut for aquaculture companies and incentives for private investment in innovation helped the shellfish industry grow sevenfold between 2003 and 2015 (Willer et al., 2021). Infrastructure combined with hatcheries with growth, purification and processing functions can further increase productivity.

Increasing consumer demand will be the driving force underpinning rapid growth of the mariculture industry, which may be achieved by improving the safety, diversity, and affordability of mariculture products. Establishing seafood quality certification systems and food safety testing programs, and technological solutions such as solar-powered UV purification systems and regular monitoring of algal bloom toxins and parasites, can enhance consumer trust in mariculture quality (Mekonnen and Hoekstra, 2012). Promoting mariculture as an affordable source of protein is also key to boosting consumer demand. In addition, culinary efforts should also be made in offering a range of diverse, delicious and non-perishable mariculture processed products to satisfy different consumer tastes.

As with all studies of this type there are some limitations. Full-scale footprint accounting needs to include all direct and indirect resource consumption and pollution discharges along the production and consumption supply chain (Zhao et al., 2019). Although a more comprehensive calculation of mariculture footprints is needed , the scope of our study and data shortages prevented us from doing so . The methods applied here provided a reasonable estimate of the footprint related to feed, which is equivalent to the boundary of the system used to calculate the footprint of LPPs. We also established a self-sufficiency and self-seclusion hypothesis, that is, assuming that both feed and mariculture products are produced and consumed only in China.

Under this assumption, we explore how much environmental impact the production of mariculture products will have on the environment. Also, whilst we've included as many important nutrients in mariculture production as possible, some important ones such as vitamin B_6 and folic acid are missing from our quantification of nutrient density. We further used the Monte Carlo method to estimate the uncertainty of the environmental footprint (See Appendix). Furthermore, we used the calculation method of nutrient density recommended by Hallstrom et al. (2019) (see Method 2.3), which assigns the same weight to different nutrients. Although this method ignores the influence of different nutrients to the human body, it is more suitable for comparison of nutritional status in different countries and regions.

5. Conclusions

Here, we conducted a detailed environmental and nutritional study on 28 mariculture products in China from data in 2018, and compared them with 7 LPPs to provide a detailed list of product environmental footprint and nutrient density score. It is hoped such a comprehensive study will help promote ecologically sensitive and efficient development of the mariculture industry in China, and provide useful indicators for development in other countries throughout the world. The findings facilitate targeted mariculture production policies, and help consumers make food choices of mariculture products that benefit the environment and health. Our research confirms China's mariculture production has environmental and nutritional advantages compared to LPPs. However, the characteristics of specific mariculture products must be considered if future mariculture industry development is to achieve more environmental, nutritional, and economic benefits. These characteristics include previously overlooked environmental indicators, nutrient content, food intake upper limits, price and production volume. Adopting the heterogeneity of different products may help policy makers identify current limitations in substituting mariculture products with LPPs.

CRediT authorship contribution statement

Shuiqin Zhang: Writing – original draft, data curation, conceptualization, formal analysis. **Xu Zhao**: Writing – review & editing, investigation, conceptualization, funding acquisition. **Kuishuang Feng**: Supervision, project administration, funding acquisition. **Yuanchao Hu**:

validation, investigation. **Martin R. Tillotson**: Writing – subsequent draft, review & editing. **Lin Yang:** review & editing, funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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